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# Design, characterization and modelling of high efficient solar powered lighting systems

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## EUPVSEC Topic 6.4: PV Applications Without a Centralized Grid

### Abstract

This paper discusses some of the major challenges in the development of L2L (Light-2-Light) products. It's the lack of efficient converter electronics, modelling tools for dimensioning and furthermore, characterization facilities to support the successful development of the products. We report the development of 2 Three-Port-Converters respectively for 1-10Wp with a peak efficiency of 99.1% at 1.5 W output power at PV to battery and almost similar characteristics for a 10-50 Wp. Furthermore, a modelling tool for L2L products has been developed and a laboratory for feeding in component data not available in the datasheets to the model is described. A living lab facility is realized to field test prototypes of L2L lighting products in their development state to validate the modelling tool and tweak the parameters in the system for optimized performance the product.

### Introduction

The last few year significant progress has been made in research and development of renewable systems. Solar energy is one of the most reliable, daily available and environment friendly renewable energy source, being unlimited, clean and free [1], [2]. Furthermore, due to the ability to generate off-grid electricity, sustainable energy systems have attracted research interest in the last decades [3]. Due to the rapid increasing efficiency of light emitted diodes (LEDs) stand-alone combinations of PV module, battery storage and LED luminaires is becoming more attractive for a variety of lighting applications [4]. The systems operates entirely on DC and is often called Light-to-light (L2L) systems, see Fig. 1. Park lights and bollards are examples of L2L systems and these systems offers lighting solutions, for places where lighting is not feasible due to very high cabling costs of up to e.g. 700 €/m in Copenhagen and up to 2000€/m in Berlin [5]. Some of the major obstacles still remaining for successful L2L systems are 1) lack of efficient conversion electronics for small PV systems, (PV powers of 1-50 Wp) 2) lack of a dimensioning and assessment tool for L2L systems and 3) knowledge centers and laboratory facilities for supporting the complicated process of designing successful L2L products. The latter being an interdisciplinary technical task involving at least knowledge, tools, and test equipment for the technology fields of lighting, photovoltaics and power electronics. A series of Danish research projects has addressed these issues and the results are reported here.

### Electronic Converter

An electronic converter for outdoor light-to-light purposes should be able to work in two modes:

1. In the daytime: Convert energy from the PV panel while maintaining Maximum Power Point Tracking (MPPT) in order to harvest as much energy to the battery from the available solar energy as possible.
2. In the night: Convert stored energy from the battery to the operating point of the LED panel.

Hence this application calls for a Three-Port-Converter (TPC) with two operating modes as sketched in Fig. 2.

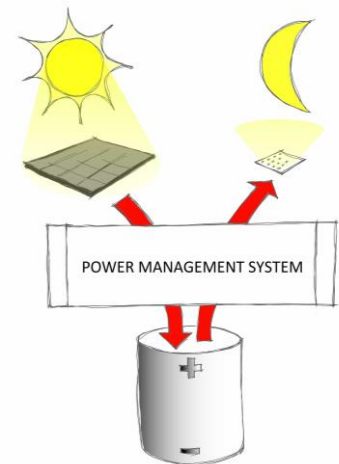


Fig. 1. A principle sketch of a Light-2-Light system.

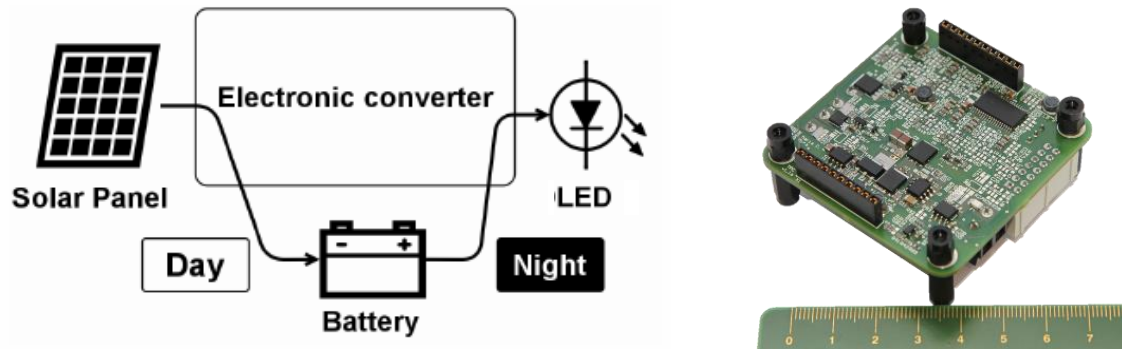


Fig. 2. Working principle of the converter (left) and image of prototype of 1-10 Wp converter (right)

To cover the full range of 1-50 Wp of solar panels with high efficiency, 2 versions of converters was developed. A low range for PV powers 1-10 Wp and a high power range of 10-50 Wp, giving the versatility of choosing solar panels in the whole span. The efficiency curve for the 10 Wp version is shown in Fig. 3. It is sought to achieve the peak conversion efficiency in the lower part of its operating range since L2L products often are placed in areas with a lot of shadows on the solar panels e.g. in parks or in the urban environments, making peak power operation rare.

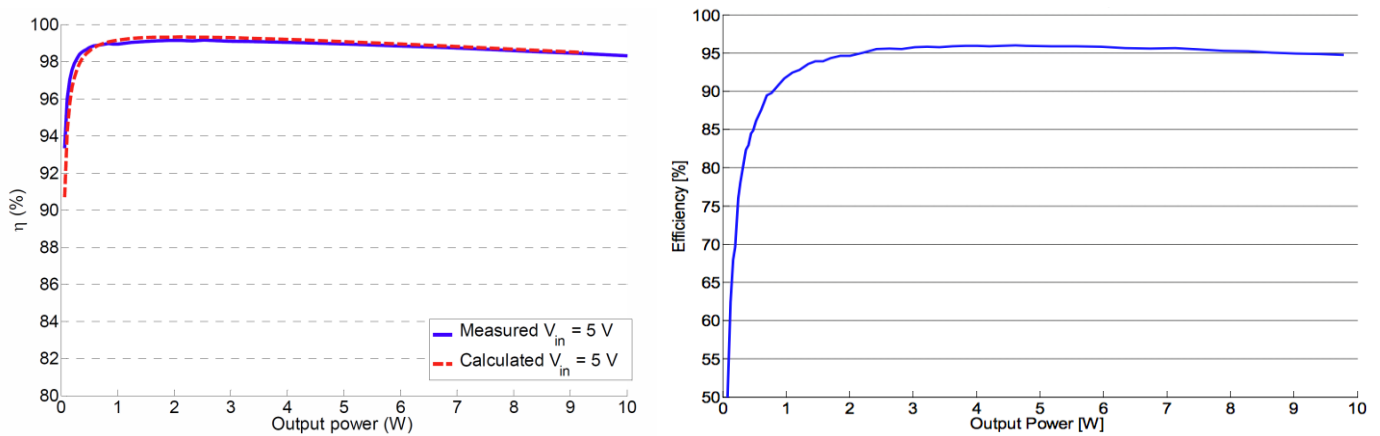


Fig. 3. Efficiency curve of the 10 W converter when harvesting energy from PV panel to the battery (left). It can be seen that the converter excels in having its highest efficiency at the lowest power obtaining >99% from 1.2W to 4W output power. The curve (right) shows the LED driver stage efficiency peaking at 3W output power with 97.3%.

The converters peak efficiency is 99.1 % when operating at 1.5 W. The output power and the LED driver stage present a peak efficiency of 97.3% at 3W output power. The electronics converter work is documented in [6] and [7].

### Software for dimensioning and simulation of PV LED applications

The authors have investigated several software tools on the market and none was found suited for the task of dimensioning and simulating performance of solar powered L2L products. A customized tool is therefore developed in MATLAB as a starting point with input from several specialized tools. The block diagram, Fig. 4, shows the design of the simulation tool, which essentially is a computer model of a basic PV application, including PV panel, electronics, battery and power consumption in the form of an LED luminaire. The L2L dimensioning tool differs since it uses highly time resolved weather data in 1-minute resolution. This is important when modelling solar products operating most of its time in the shadows from buildings and other artefacts. The efficiency curve, Fig. 3, of the developed converter is rather flat in the whole irradiation interval from 0-1 sun. The full electronic controller unit, however, consist of both converter and controller with a microcontroller operating in several states, running algorithms, and controlling other external devices as a battery management system, motions sensors etc. The real energy conversion functions are therefore usually far from linear and depend heavily on irradiation level on the PV panel, temperature, battery voltage and other parameters which need to be modelled for precision. The energy flow is basically made up of

1. Energy flow from the sun to the PV panel
2. Energy flow from the panel – through the charger – and into the battery
3. Energy flow from the battery – through the discharger – into the LEDs
4. Stand-by consumption of the electronics controller due the intelligent disposition of the energy for lighting (the lighting scheme) and the loss in its external components (if any).

The datasheets of small solar panels, PV/LED controllers and batteries are rarely having data for this type of modelling to be done.

### Laboratory for characterization of L2L products

A specialized laboratory has been built, to feed the mathematical simulation tool with accurate and sufficient data for modelling of L2L products and support the development of successful solar powered LED products. It is composed of the following facilities

#### Component characterization

- Solar cell electrical (I, V, Irradiation 0-1 sun AM 1.5)
- Solar panel electrical (I, V, Irradiation 0-1 sun AM 1.5)
- Battery (I, V, Charge, Temp)
- LED electrical and photometrical (I, V, lumens)
- Electronics controller
  - Charging efficiency (Emulation of the PV panel and the battery, allowing mapping of the full operating range for the charger)
  - Discharge efficiency ( $V_{bat}$ ,  $I_{LED}$ ,  $V_{LED}$ )
- Shade measurement/simulation

#### Luminaire characterization

- Spectroradiometry
- Photometry
- Goniospectroradiometry
- Goniophotometry

The measurements are tailored to fit into the L2L modelling tool and are more or less automated to characterize the individual components in the many different operating states needed. The luminaire characterization is not part of the model but a part of the process of creating highly efficient high end L2L products. The light rays need to illuminate the desired object nicely without the light being lost in reflectors and diffusers, giving rise to glare or other waste mechanisms. Here good optical engineering can reduce the total amount of light needed, and thus improving the efficiency. The relevant metric is useful lux or useful lumens which can be modelled by use of e.g. DIALux and RELUX which can be used iteratively with the L2L model.

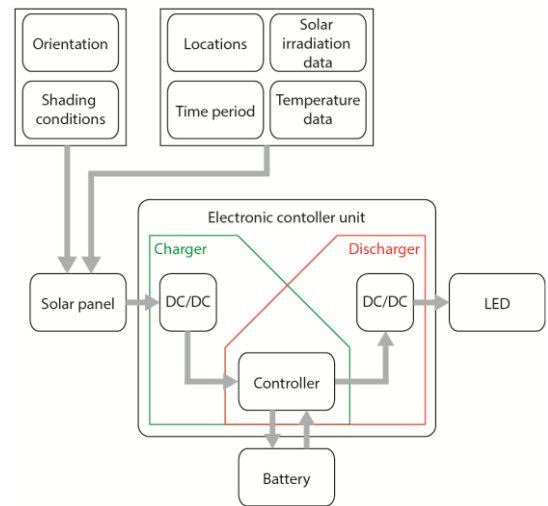


Fig. 4. Block diagram of L2L modelling tool.

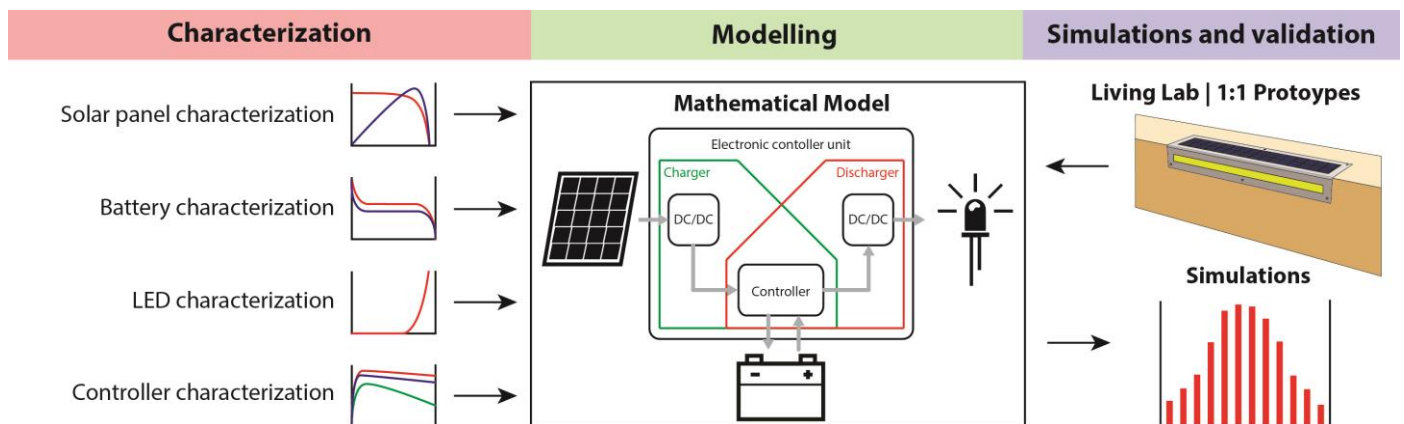


Fig. 5. Diagram of the data feed-back loop for simulation of L2L products and validation of the model.

## L2L - Living Lab

A living lab for installation and monitoring the energy flow inside the L2L products is made and will be expanded in the coming years the university campus of the Technical University of Denmark around the building of Department of Photonics Engineering in Roskilde. The modelling tool can thereby be validated against periods with known weather data where data logging has been implemented in the products. The differences between simulated performance of a product and the logged performance is due to inaccuracies in the model and is a valuable tool to optimize it. The validation process will be disclosed later in a publication. Fig. 5. shows the data feed-back loop.

## Prototype development of L2L products

Several products have been designed parallel in the process of developing the L2L converter electronics, the L2L simulation tool and L2L laboratory and living lab. The products were developed together with the company, Outsider, who is designing, producing and distributing high-end solar powered lighting product for the urban environments. 2 Products were developed together with Outsider and the Architecture company, Snøhetta, for the King Abdulaziz Centre for World Culture in Dhahran Saudi Arabia, see Fig. 6 (left). below.



Fig. 6. King Abdulaziz Center for World Culture - Rendering Snøhetta/Mir (left). LIGHT-TUBE (right)

One of the products are called LIGHT-TUBE and is inspired by bulrushes swaying gently in the wind, shown Fig. 6 (right). Especially the shade modelling was a special challenge of this product along with temperature modelling of the systems that had to be done to fit the data to the model. The PV is integrated in the base of the product and the LEDs in the end of the metal stick where luminaires is composed of edge-lit acrylic wave guides, sandblasted on the sides.

## Conclusion

3 major challenges in the development of L2L products is the lack of efficient converter electronics, modelling tools for dimensioning and furthermore, characterization facilities to support the successful development of the products. Above we report the development of 2 Three-Port-Converters respectively for 1-10Wp and 10-50 Wp PV panels with a peak efficiency of 99.1% at 1.5 W of output power for the 10 Wp version PV to battery conversion state. Furthermore, a modelling tool for L2L products has been described and a laboratory for feeding in component data not available in the datasheets to the model is described. A living lab for field test of L2L product to validate the modelling tool and assisting in the development process of L2L products is also under development.

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